Final report for NAG5-11294
Simple models of the spatial distribution of cloud radiative properties for remote sensing studies"

This project aimed to assess the degree to which estimates of three-dimensional cloud structure can be inferred from a time series of profiles obtained at a point. The work was motivated by the desire to understand the extent to which high-frequency profiles of the atmosphere (e.g. ARM data streams) can be used to assess the magnitude of non-plane parallel transfer of radiation in the atmosphere. We accomplished this by performing an observing system simulation using a large-eddy simulation and a Monte Carlo radiative transfer model.

We define the "3D effect" as the part of the radiative transfer that isn't captured by one-dimensional radiative transfer calculations. We assess the magnitude of the 3D effect in small cumulus clouds by using a fine-scale cloud model to simulate many hours of cloudiness over a continental site. We then use a Monte Carlo radiative transfer model to compute the broadband shortwave fluxes at the surface twice, once using the complete three-dimensional radiative transfer F^{3D}, and once using the ICA F^{ICA}); the difference between them is the 3D effect

$$\Delta F^{3D} \equiv F^{ICA} - F^{3D}. \tag{1}$$

Simulating evolving cloud fields

We simulate the development of shallow convection using a large eddy simulation developed by Bjorn Stevens at UCLA. In our experiments the model is configured with grid spacings of 50 m in the horizontal and 40 m in the vertical. The domain extends 8 km horizontally and from the surface to 4.36 km. Boundary conditions in the horizontal are periodic. Clouds form and dissipate through condensation and evaporation.

The model is initialized with small random perturbations in the potential temperature field. We make three sets of runs, each with a different velocity profile for the applied large-scale wind. In "constant wind" runs the wind blows from the west at 5 m/s throughout the domain. In "speed shear" runs wind direction is constant but velocity increases from 3.5 m/s near the surface to 7.8 m/s at the top of the model; the region in which most clouds develop has a mean large-scale wind speed near 5 m/s. In "directional shear" runs the applied wind speed is held fixed at 5 m/s but the direction varies from westerly near the ground to southerly at the top of the domain

The model is run for up to 12 hours at a time. Surface fluxes of latent and sensible heat, along with advective tendencies for temperature and water, are prescribed based on observations obtained around a continental site in June. Three-dimensional fields of the atmospheric state, including cloud liquid water content, are saved every five minutes once clouds have begun to form. We simulate observations by a perfect set of profiling instruments by recording the state of the central column in the domain every ten seconds. We create different cloud field realizations by varying the initial potential temperature perturbations and running the model again. Our final dataset comprises about 210 hours of cloud evolution, divided roughly evenly among the three wind velocity profiles.

Simulating radiative fluxes in inhomogeneous clouds

We make ICA and three-dimensional radiative transfer calculations using a single Monte Carlo model. We compute broadband fluxes by integrating over 13 bands in the spectral range 0.16 μm to 7.6 μm weighted according the incoming solar flux. Cloud optical properties within each LES grid cell are determined from cloud liquid water content by assuming a constant drop number concentration of 200 per cubic centimeter and a gamma droplet size distribution with an effective variance of 0.1. Cloud single scattering properties (extinction, single scattering albedo, and scattering phase function) are tabulated for each spectral band using Mie theory. Gaseous absorption is treated using the shortwave Rapid Radiative Transfer Model using mixing ratio profiles extending from the surface to 40 km. Surface albedo varies with wavelength. The code uses the maximal cross-section method for three separate layers (above, below, and in the cloud levels). We use 10^6 photons for each scene, which yields flux accuracies of about 0.3% in homogeneous clouds, and presumably greater accuracy in domain-averaged fluxes when cloud fraction is small.

Simulating observations by profiling instruments

We simulate observations by a perfect instrument by extracting the time series of cloud properties in the cloud model's central column every ten seconds. We interpret these as two-dimensional slices of cloudiness by choosing a constant advection velocity v, and assigning a spatial width of $\Delta x = v\Delta t$ to profiles separated by time intervals Δt. We call these cross-sections "soda straws," to indicate that they have been constructed from individual columns. These cross-sections can be accumulated over any time interval; we have examined windows of 30 minutes, one hour, and three hours.

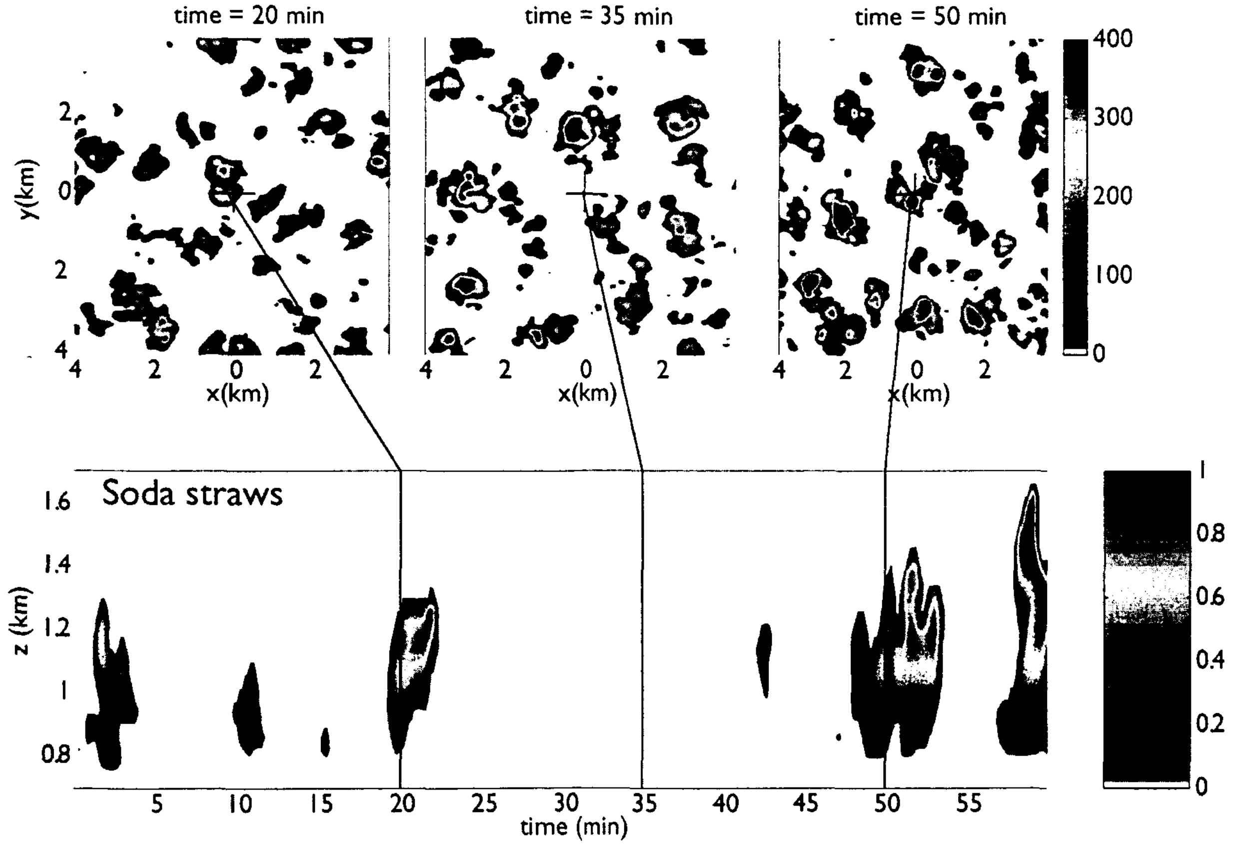

Figure 1: Three snapshots of cloud evolution during the course of a large-eddy simulation of shallow convection over a continental site, and the cloud field that would be observed by a perfect profiling instrument at the center of the domain. The upper panels show liquid water path in g/m^2; the lower panel liquid water content in g/m^3. We estimate the magnitude of the three dimensional effect in both sets of clouds.

The same question arises for us as for those using real observations in this way: what value of v provides the best mapping from time to space? We try to make the fewest possible assumptions. We compute an average wind speed for each time interval by weighting the actual wind speed by the liquid water content q_l as a function of height and time.

$$\bar{v} = \int_{t_i}^{t_f} v(t, z) q_l(t, z) dt$$

where both quantities are averaged over the horizontal domain at each level and each time step. We assume that v equals the advection speed v, and ignore the effects of varying wind *direction*, even in those runs with directional shear in the applied winds. The conversion from time to space (i.e. the horizontal distance each profile represents) is constant for a given time interval (now a 2D scene) but varies between intervals.

What causes errors in estimate of the 3D effect made from series of profiles?

We can assess the overall error in estimates of the 3D effect made from a time series of profiles by subtracting the 3D effect estimated from the 3D, time evolving scenes (i.e. "the truth") during some time interval from the 3D effect inferred from the soda straws accumulated over the same time; that is

$$\Delta(\Delta F^{3D}_{\text{total}}) = \Delta F^{3D}_{\text{soda straws}} - \Delta F^{3D}_{3D}$$

By performing radiative transfer calculations on various subsets of the time-evolving, three-dimensional cloud fields produced by the large eddy simulation, we are able to decompose this error in the 3D effect into three parts: the impact of the frozen turbulence assumption, the impact of under-sampling by a profiling instrument, and the difficulty in estimating the magnitude of the 3D effect from a two-dimensional slice of clouds:

$$\Delta(\Delta F^{3D}_{\text{total}}) = \Delta(\Delta F^{3D}_{\text{frozen turb.}}) + \Delta(\Delta F^{3D}_{\text{sampling}}) + \Delta(\Delta F^{3D}_{\text{2D}}$$

The relative importance of these three factors, averaged over all one-hour intervals as a function of solar illumination angle, is shown in FIGURE. Both the frozen turbulence assumption and under-sampling introduce large amounts of noise into a the estimate made for any particular hour, but these errors tend to cancel out over time. Almost all of the systematic error arises from the lack of knowledge about cloud structure in the third dimension. This causes an overestimate of the 3D effect when the sun is high and an underestimate when the sun is low.

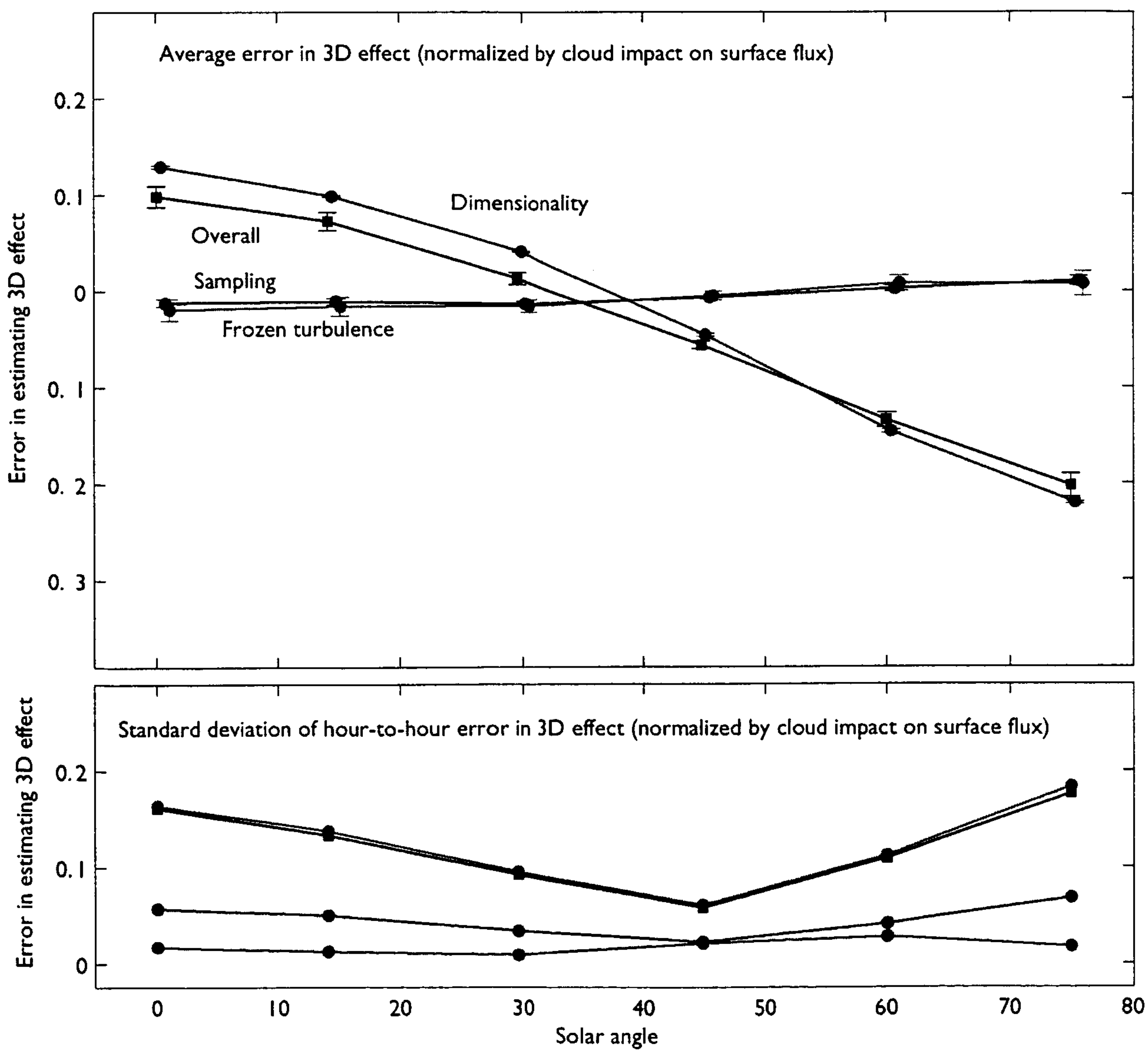

Figure 2: Mean error and hour-to-hour variability in the ability to estimate the 3D effect

Implications

Long-term observations by ground-based profilers can provide an invaluable source of information on cloud macro-structure and internal variability. Given long enough, the profiling instruments capture essentially all of the variability that exists in the full cloud fields, and can effectively use the frozen turbulence assumption to determine the two-dimensional cloud structure. We have shown, however, that these records can not be used without further manipulation to estimate the magnitude of the 3D effect in scattered clouds, because the profilers are unable to produce information about cloud variability (and especially cloud edges) in the direction perpendicular to the advection. This implies the need for statistical methods capable of extending the observed variability into the third dimension.

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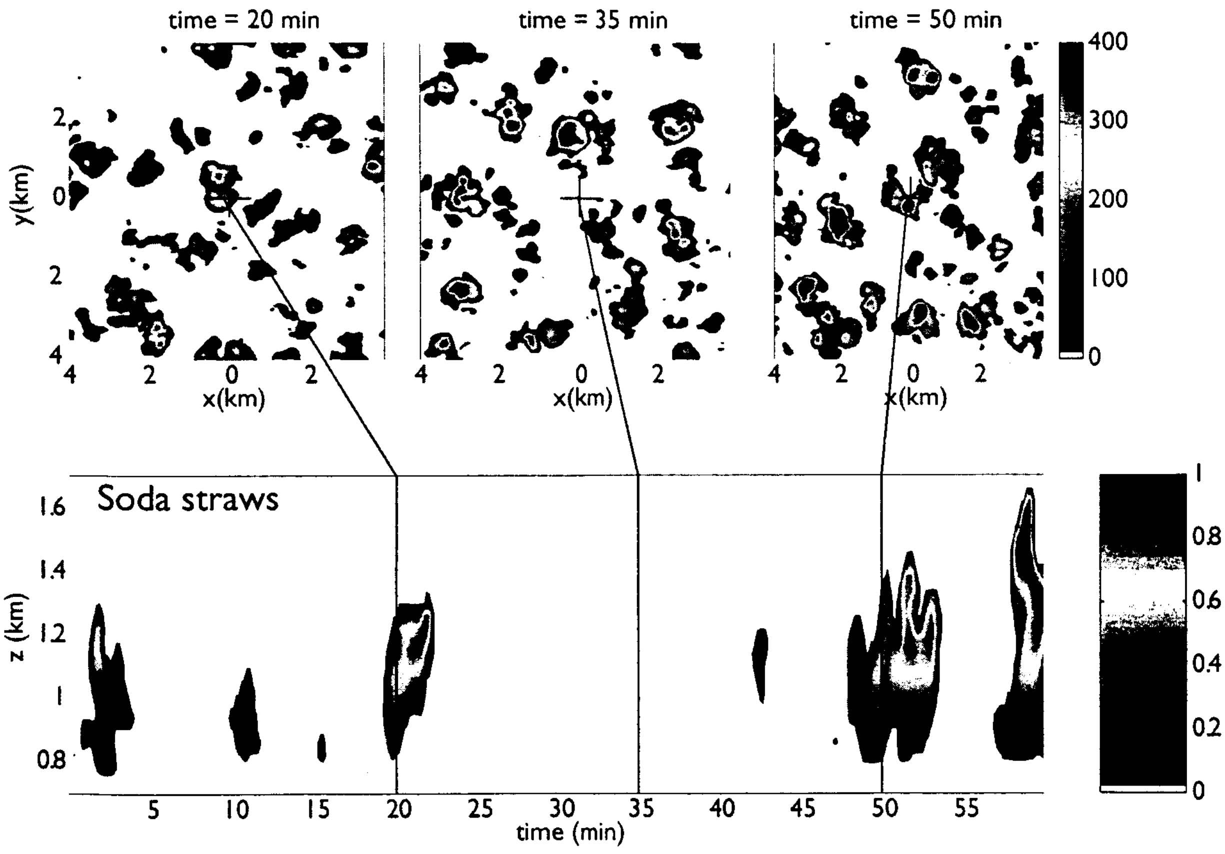

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